

$f_0(980)$ and $a_0(980)$ resonances near $\gamma\gamma \rightarrow K^+K^-$ and $\gamma\gamma \rightarrow K^0\bar{K}^0$ reaction thresholds

N.N. Achasov* and G.N. Shestakov†

Laboratory of Theoretical Physics, S.L. Sobolev Institute for Mathematics, 630090, Novosibirsk, Russia

High-statistics data on the reactions $\gamma\gamma \rightarrow K^+K^-$ and $\gamma\gamma \rightarrow K^0\bar{K}^0$ are the last missing link in investigations of the light scalar mesons $f_0(980)$ and $a_0(980)$ in photon-photon collisions. It is believed that $f_0(980)$ and $a_0(980)$ resonances exhibit their four-quark structure in these reactions in a very peculiar way. The work estimates the feasibility of measurements of scalar contributions near $\gamma\gamma \rightarrow K^+K^-$ and $\gamma\gamma \rightarrow K^0\bar{K}^0$ reaction thresholds at modern colliders.

PACS numbers: 12.39.-x, 13.40.-f, 13.60.Le, 13.75.Lb

A major contribution to understanding the nature of light scalar mesons $\sigma(600)$, $f_0(980)$, and $a_0(980)$ (which are candidates for four-quark states) has come from the physics of photon-photon collisions, a field which has recently entered the era of high-precision statistics (see, for example, a recent review [1]). It has been opened by the unprecedented series of measurements of the $\gamma\gamma \rightarrow \pi^+\pi^-$ [2, 3], $\gamma\gamma \rightarrow \pi^0\pi^0$ [4], $\gamma\gamma \rightarrow \pi^0\eta$ [5], and $\gamma\gamma \rightarrow \eta\eta$ [6] reaction cross sections, performed by the Belle Collaboration at KEKB. The statistics collected in these experiments is two to three order of magnitude higher than in pre- B -factory measurements. Recently, the two-photon production of the $\pi^0\eta$ system has been also investigated by the BABAR Collaboration at PEP-II [7].

Extensive programs on the two-photon physics, aimed, in particular, at continuing precision measurements of the $\gamma\gamma \rightarrow \pi^+\pi^-$, $\gamma\gamma \rightarrow \pi^0\pi^0$, and $\gamma\gamma \rightarrow \pi^0\eta$ processes in the $\sigma(600)$, $f_0(980)$, and $a_0(980)$ resonance region, are preparing for realization at the upgraded collider BEPCII (with a luminosity of $10^{33} \text{ cm}^{-2} \text{ sec}^{-1}$) with the use of the BES-III detector [8] and at the upgraded ϕ -factory DAΦNE (with a luminosity of $(1-5) \times 10^{32} \text{ cm}^{-2} \text{ sec}^{-1}$) with the use of the KLOE-2 detector [9–13].

Similar two-photon experiments are also possible at the VEPP-4M accelerator with the KEDR detector [14] and at the VEPP-2000 accelerator (with a luminosity of $10^{32} \text{ cm}^{-2} \text{ sec}^{-1}$) with the detectors CMD-3 [15] and SND [16].

High-statistic information is still lacking for the $\gamma\gamma \rightarrow K^+K^-$ and $\gamma\gamma \rightarrow K^0\bar{K}^0$ processes in the energy range around 1 GeV. It is believed that $f_0(980)$ and $a_0(980)$ resonances exhibit their four-quark structure in these processes in a very peculiar way [17–19].

Experiments show that the cross sections of $\gamma\gamma \rightarrow K^+K^-$ [20–25] and $\gamma\gamma \rightarrow K_S^0\bar{K}_S^0$ [20, 24, 26–31] reactions in an energy range of $1.2 < \sqrt{s} < 1.7$ GeV (\sqrt{s} is the invariant mass of the $\gamma\gamma$ system) are actually saturated with the contributions from classical

tensor $f_2(1270)$, $a_2(1320)$, and $f_2'(1525)$ resonances produced in helicity states with $\lambda = \pm 2$. Constructive and destructive interference between $f_2(1270)$ - and $a_2(1320)$ -resonance contributions are observed in $\gamma\gamma \rightarrow K^+K^-$ and $\gamma\gamma \rightarrow K^0\bar{K}^0$ reactions, respectively, in agreement with the $q\bar{q}$ model prediction [32]. The energy region near the $K\bar{K}$ thresholds, $2m_K < \sqrt{s} < 1.1$ GeV, sensitive to the S -wave contributions, remains virtually unexplored. In the ARGUS experiment [23], the efficacy of recording K^+K^- events for $2m_{K^+} < \sqrt{s} < 1.1$ GeV was negligible, while the statistics in the L3 experiment [30] on the $\gamma\gamma \rightarrow K_S^0\bar{K}_S^0$ reaction for $2m_{K^0} < \sqrt{s} < 1.1$ GeV did not exceed 10 events. The available data from other experiments relate to the region of $\sqrt{s} > 1.2$ GeV. Note that the tensor resonance contributions are strongly suppressed for $2m_K < \sqrt{s} < 1.1$ GeV due to the D -wave threshold factor $p_K^5(s) = (s/4 - m_K^2)^{5/2}$. A simple estimate shows that the $\gamma\gamma \rightarrow K^+K^-$ cross section, corresponding to all tensor contributions (including the Born contribution), makes $\approx [p_{K^+}^5(s)/p_{K^+}^5(1.21 \text{ GeV}^2)] \times 2 \text{ nb}$ for $2m_{K^+} < \sqrt{s} < 1.1$ GeV [23]. The $\gamma\gamma \rightarrow K^0\bar{K}^0$ cross section in this region, caused by the tails of tensor mesons, is at least twenty times smaller. Figure 1 illustrates the scale of the K^+K^- production cross section observed in $\gamma\gamma$ collisions in the tensor meson region.

The absence of an appreciable nonresonant background in the $\gamma\gamma \rightarrow K^+K^-$ cross section seems at first sight rather surprising, since the Born contribution mediated through the charged one-kaon exchange mechanism and comparable with the tensor resonance contributions must be present in this channel, see the solid curves in Fig. 1. This figure also shows that the Born cross section [both for the elementary (point-like) K^\pm exchange and for the K^\pm exchange with a form factor] is dominated by the S -wave contribution for $2m_{K^+} < \sqrt{s} < 1.5$ GeV. For this reason, a large non-coherent background could be expected under tensor meson peaks in the K^+K^- channel. However, taking account of the resonant interaction between K^+ - and K^- -mesons in the final state results in the compensation of a considerable part of this background [18, 19]. The compensation arises in the following way. Due to the contribution from the $\gamma\gamma \rightarrow K^+K^- \rightarrow K^+K^-$ rescattering

*E-mail: achasov@math.nsc.ru

†E-mail: shestako@math.nsc.ru

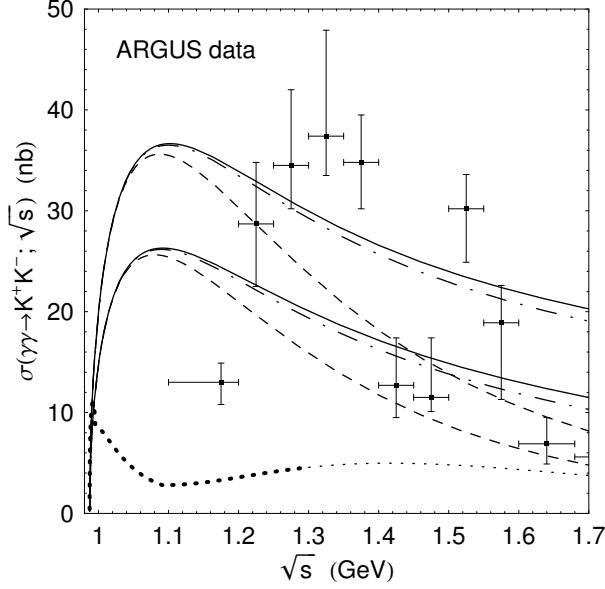


Figure 1: Illustration of the scale of the K^+K^- production cross section in $\gamma\gamma$ collisions. The data are from ARGUS [23]. The upper dashed, dashed-dot, and solid curves correspond to the Born $\gamma\gamma \rightarrow K^+K^-$ cross section for the elementary (point-like) one-kaon exchange with $\lambda J = (00, (00 \text{ and } 22))$ and to the total Born cross section, respectively (the Born contribution with $\lambda J = 02$ is negligible); here λ is the sum of helicities of initial photons and J is their total angular momentum. The lower dashed, dashed-dot, and solid curves show the same cross section modified by the form factor [1, 18, 19]. The dotted curve is our estimate of the S -wave $\gamma\gamma \rightarrow K^+K^-$ cross section [1].

tering amplitude with real kaons in the intermediate state, the Born S -wave $\gamma\gamma \rightarrow K^+K^-$ amplitude acquires the factor $\xi(s) = [1 + i\rho_{K^+}(s)T_{K^+K^- \rightarrow K^+K^-}(s)]$, where $\rho_{K^+}(s) = 2p_{K^+}(s)/\sqrt{s}$. Near the K^+K^- threshold, the S -wave $T_{K^+K^- \rightarrow K^+K^-}(s)$ amplitude is dominated by contributions from $f_0(980)$ and $a_0(980)$ resonances. Given their strong coupling to $K\bar{K}$ -channels, naturally realized in the four-quark scheme, the $T_{K^+K^- \rightarrow K^+K^-}(s)$ amplitude possesses an appreciable imaginary part. As a result, factor $|\xi(s)|^2$ just above the K^+K^- threshold is much smaller than unity and the seed S -wave Born contribution is compensated for over a wide \sqrt{s} range. The dotted curve in Fig. 1 represents our estimate of the S -wave $\gamma\gamma \rightarrow K^+K^-$ cross section [1], which fairly well agrees with the ones obtained in earlier studies [18, 19]. The validity of these estimates can be expected at least for $\sqrt{s} \lesssim 1.3$ GeV (see Fig. 1).

Thus, one can hope to detect scalar contributions at the level of 5–10 nb in the $\gamma\gamma \rightarrow K^+K^-$ cross section for $2m_{K^+} < \sqrt{s} < 1.1$ GeV. As regards the $\gamma\gamma \rightarrow K^0\bar{K}^0$ reaction, its amplitude does not contain the Born contribution, while the $a_0(980)$ -resonance contribution has the sign opposite to that in the $\gamma\gamma \rightarrow K^+K^-$ channel. As a result, the contributions of S -wave $\gamma\gamma \rightarrow K^+K^- \rightarrow K^0\bar{K}^0$ rescattering amplitudes with

Table I: Estimates of $N_{eeK^+K^-}$ for four values of E_{cm} and L_{ee} , and for two intervals of integration in Eq. (1) $(\Delta\sqrt{s})_1: 2m_{K^+} < \sqrt{s} < 1.05$ GeV and $(\Delta\sqrt{s})_2: 2m_{K^+} < \sqrt{s} < 1.1$ GeV.

E_{cm}	L_{ee}	$(\Delta\sqrt{s})_1$	$(\Delta\sqrt{s})_2$
2 GeV	$1 fb^{-1}$	0.56×10^3	0.74×10^3
2.4 GeV	$5 fb^{-1}$	4.1×10^3	5.5×10^3
3.77 GeV	$5 fb^{-1}$	8.7×10^3	11.7×10^3
10.58 GeV	$100 fb^{-1}$	5.1×10^5	6.9×10^5

isospin $I=0$ and 1 in the $\gamma\gamma \rightarrow K^0\bar{K}^0$ reaction practically cancel each other and the corresponding cross section should be at the level of $\lesssim 1$ nb.¹

The number of two-photon events, N_{eeX} , produced in the $e^+e^- \rightarrow e^+e^-X$ reaction, when e^+ and e^- in the final state are not registered, can be evaluated according to (see, for example, Refs. [8–10])

$$N_{eeX} = L_{ee} \int_{\Delta\sqrt{s}} \frac{dF}{d\sqrt{s}} \sigma(\gamma\gamma \rightarrow X; \sqrt{s}) d\sqrt{s}, \quad (1)$$

where L_{ee} is the e^+e^- integrated luminosity, $\Delta\sqrt{s}$ is the interval of integration over the $\gamma\gamma$ invariant mass, and $dF/d\sqrt{s}$ is the effective $\gamma\gamma$ luminosity per unit energy,

$$\frac{dF}{d\sqrt{s}} = \frac{1}{\sqrt{s}} \left(\frac{2\alpha}{\pi} \right)^2 \left(\ln \frac{E_{cm}}{2m_e} \right)^2 f(z), \quad (2)$$

where E_{cm} is the energy in the e^+e^- center-of-mass system, $f(z) = -(z^2 + 2)^2 \ln z - (1 - z^2)(3 + z^2)$, and $z = \sqrt{s}/E_{cm}$.

Estimates of the number of events of two-photon production of K^+K^- pairs in the S -wave, $N_{eeK^+K^-}$, are presented in Table I for working values of E_{cm} and probable values of L_{ee} for detectors CMD-3 and SND (VEPP-2000, 2 GeV), KLOE-2 (DAΦNE, 2.4 GeV), BES-III (BEPCII, 3.77 GeV), Belle (KEKB, 10.58 GeV), and BABAR (PEP-II, 10.58 GeV). They show that study of scalar contributions in the $\gamma\gamma \rightarrow K^+K^-$ reaction near the threshold can become quite wealthy at modern colliders (currently, data on these contributions are absent).

¹ Recall that the classical tensor $f_2(1270)$, $a_2(1320)$, and $f'_2(1525)$ mesons couple to photons via direct $q\bar{q} \rightarrow \gamma\gamma$ transitions, whereas the couplings of the light scalar $\sigma(600)$, $f_0(980)$, and $a_0(980)$ mesons to $\gamma\gamma$ are realized owing to the four-quark transitions (rescattering mechanisms) of the type $\sigma(600) \rightarrow \pi^+\pi^- \rightarrow \gamma\gamma$, $f_0(980) \rightarrow K^+K^- \rightarrow \gamma\gamma$, $a_0(980) \rightarrow (K^+K^-, \pi^0\eta) \rightarrow \gamma\gamma$, and the direct $\sigma(600) \rightarrow \gamma\gamma$, $f_0(980) \rightarrow \gamma\gamma$, and $a_0(980) \rightarrow \gamma\gamma$ transitions are small [1]. Opportunity to explain the suppression of the large S -wave Born contribution in $\gamma\gamma \rightarrow K^+K^-$ by that of the $f_0(980)$ and $a_0(980)$ resonances, $\gamma\gamma \rightarrow K^+K^- \rightarrow [f_0(980) + a_0(980)] \rightarrow K^+K^-$, indicates in favor of this picture and, consequently, in favor of the $q^2\bar{q}^2$ nature of the $f_0(980)$ and $a_0(980)$ states.

The number of events in the $K_S^0 \bar{K}_S^0$ channel can be expected at least an order of magnitude smaller. But even establishing a reliable upper limit on the S -wave $\gamma\gamma \rightarrow K^0 \bar{K}^0$ cross section near the threshold will be very important for the selection of theoretical models that have simultaneously to describe the reactions $\gamma\gamma \rightarrow \pi^+ \pi^-$, $\gamma\gamma \rightarrow \pi^0 \pi^0$, $\gamma\gamma \rightarrow \pi^0 \eta$, $\gamma\gamma \rightarrow K^+ K^-$, and

$\gamma\gamma \rightarrow K^0 \bar{K}^0$ in the $f_0(980)$ and $a_0(980)$ resonance region.

This work was supported in part by RFBR, Grant No 10-02-00016, and Interdisciplinary project No 102 of Siberian division of RAS.

-
- [1] N.N. Achasov and G.N. Shestakov, Usp. Fiz. Nauk **181**, 827 (2011) [Physics–Uspekhi **54**, 799 (2011)].
 - [2] T. Mori, S. Uehara, Y. Watanabe et al., Phys. Rev. D **75**, 051101(R) (2007).
 - [3] T. Mori, S. Uehara, Y. Watanabe et al., J. Phys. Soc. Jpn. **76**, 074102 (2007).
 - [4] S. Uehara, Y. Watanabe, I. Adachi et al., Phys. Rev. D **78**, 052004 (2008).
 - [5] S. Uehara, Y. Watanabe, H. Nakazawa et al., Phys. Rev. D **80**, 032001 (2009).
 - [6] S. Uehara, Y. Watanabe, H. Nakazawa et al., Phys. Rev. D **82**, 114031 (2010).
 - [7] P. del Amo Sanchez, J. P. Lees, V. Poireau et al., Phys. Rev. D **84**, 052001 (2011).
 - [8] D.M. Asner, T. Barnes, J. M. Bian et al., Int. J. Mod. Phys. A **24** S1 (2009).
 - [9] G. Venanzoni, Chinese Phys. C **34**, No.6, 918 (2010).
 - [10] G. Amelino-Camelia, F. Archilli, D. Babusci et al., Eur. Phys. J. C **68** 619 (2010).
 - [11] D. Babusci, C. Bini, F. Bossi et al., arXiv:1007.5219 [hep-ex].
 - [12] E. Czerwinski, Nucl. Phys. B Proc. Suppl. **207-208**, 137 (2010).
 - [13] F. Archilli, D. Babusci, D. Badoni et al., arXiv:1107.3782 [hep-ex].
 - [14] V.V. Anashin, V.M. Aulchenko, E.M. Baldin et al., Chinese Phys. C **34**, No.6, 650 (2010).
 - [15] E.P. Solodov, arXiv:1108.6174 [hep-ex].
 - [16] P.M. Astigeevich, M.N. Achasov, V.M. Aulchenko et al., Preprint BINP 2011-21, Novosibirsk 2011; <http://vepp2k.inp.nsk.su>.
 - [17] N.N. Achasov and G.N. Shestakov, Usp. Fiz. Nauk **161**, No.6, 53 (1991). [Sov. Phys. Usp. **34**, No.6, 471 (1991)].
 - [18] N.N. Achasov and G.N. Shestakov, Yad. Fiz. **55**, 2999 (1992) [Sov. J. Nucl. Phys. **55**, 1677 (1992)].
 - [19] N.N. Achasov and G.N. Shestakov, Mod. Phys. Lett. A **9** 1351 (1994).
 - [20] M. Althoff, R. Brandelik, W. Braunschweig et al., Phys. Lett. B **121** 216 (1983).
 - [21] R.P. Johnson, Ph.D. thesis, Stanford University, SLAC-Report-294, 1986.
 - [22] H. Aihara, M. Alston-Garnjost, R.E. Avery et al., Phys. Rev. Lett. **57** 404 (1986).
 - [23] H. Albrecht, H. Ehrlichmann, G. Harder et al., Z. Phys. C **48**, 183 (1990).
 - [24] M. Feindt and J. Harjes, Nucl. Phys. B Proc. Suppl. **21**, 61 (1991).
 - [25] K. Abe, K. Abe, T. Abe et al., Eur. Phys. J. C **32**, 323 (2004).
 - [26] M. Althoff, W. Braunschweig, F.J. Kirschfink, et al., Z. Phys. C **29** 189 (1985).
 - [27] Ch. Berger, H. Genzel, W. Lackas et al., Z. Phys. C **37**, 329 (1988).
 - [28] H.-J. Behrend, L. Criegee, J.B. Dainton et al., Z. Phys. C **43**, 91 (1989).
 - [29] S. Braccini, Acta Phys. Polon. B **31**, 2143 (2000).
 - [30] M. Acciarri, P. Achard, O. Adriani et al., Phys. Lett. B **501**, 173 (2001).
 - [31] H.C. Huang, arXiv:hep-ex/0104024.
 - [32] D. Faïman, H.J. Lipkin, and H.R. Rubinstein, Phys. Lett. B **59**, 269 (1975).